STUDY & SIMULATION OF DIRECT TORQUE CONTROL METHOD FOR THREE PHASE INDUCTION MOTOR DRIVES

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ABSTRACT

The basic evolution of direct torque control from other drive types is explained. Qualitative comparisons with other drives are included. The basic concepts behind direct torque control are clarified. An explanation of direct self control and the field-orientation concepts implemented in the adaptive motor model block is presented. The reliance of the control method on fast processing techniques is stressed. The theoretical foundations for the control concept are provided in summary format. Information on the ancillary control blocks outside the basic direct torque control is given. The implementation of special functions directly related to the control approach is described. Finally, performance data from an actual system are presented.

Keywords – Direct Torque Control, Controller and Inverter

1. INTRODUCTION

About sixty percent of the total electrical energy generated is converted into mechanical energy, which is required whenever physical activities such as process control, transportation, industrial process etc. takes place. Electric drives are used to convert Electrical Energy into Mechanical Energy. Thus the electric drives play a very important role in every industry. [1]

Direct torque control also reestablishes direct flux control. In addition, direct torque control is implemented. A hysterisis controller controls both flux and torque. The delays associated with the PWM modulator stage are removed, since the PWM modulator is replaced by optimal switching logic. The original benefits associated with the dc drive of direct torque control, direct flux control, and high responsiveness is thus, all reestablished.
Torque response is better than that available with either dc or flux vector control. In addition, assuming moderate speed accuracy is acceptable the need for a pulse encoder is eliminated. [4]. This method is easy to implement and does not affect the ruggedness of the drive.

DIRECT TORQUE CONTROL CONCEPT

The principle of DTC for Induction motor drive is based on limit cycle control and it makes possible both quick torque response and high efficiency operation at the same time. In this system the instantaneous values of the flux and torque are calculated from only the primary variables. They can be controlled directly and independently by selecting optimum inverter switching modes. The selection is made so as to restrict the errors of the flux and torque within the hysteresis bands and to obtain the fastest torque response and highest efficiency at every instant. [2]

In an induction motor the stator flux can vary quickly compared to rotor flux. DTC makes use of this property. The DTC uses two hysteresis controllers namely flux controller and torque controller to achieve this. The control variables flux and torque are expressed in terms of stator variables. So the estimation and control of these variables becomes simple. The output of the controller determines the switch positions of the inverter which in turn accelerate or decelerate the stator flux. Hence the torque is changed at faster rate. At the same time flux controller tries to keep the operating flux around the reference value. [4]

2. BASIC DIRECT TORQUE CONTROL

Figure 2.1 shows the block diagram for a complete Direct Torque Control drive. The function of each block is as given below:

A. Speed Controller

The speed control block is implemented with a traditional proportional and integral (PI) controller. The speed reference input is compared to the actual speed feedback from the adaptive motor model. The resulting output signal, torque (speed) reference, becomes the reference for the torque reference control.

B. Torque controller

The torque reference control has two inputs, the torque (speed) reference and absolute torque reference. When the drive functions as a speed control, only the torque
(speed) reference is used. When the drive functions as a torque control, only the absolute torque reference is used. These references are never used simultaneously.

C. Torque/Flux Comparators

The torque comparator and the flux comparator are both contained in the hysteresis control block. The function of these blocks is to compare the torque reference with actual torque and the flux reference with actual flux. The adaptive motor model calculates actual levels. When actual torque drops below its differential hysteresis limit, the torque status output goes high. Likewise, when actual torque rises above its differential hysteresis limit, the torque status output goes low. Similarly, when actual flux drops below its differential hysteresis limit, the flux status output goes high, and when actual flux rises above its differential hysteresis limit, the flux status output goes low[4]

D. Optimal Switching Logic

Processing of the torque status output and the flux status output is handled by the optimal switching logic contained in the ASIC block. The function of the optimal switching logic is to select the appropriate stator voltage vector that will satisfy both the torque status output and the flux status output. In reality, there are only six voltage vectors and two zero-voltage vectors that a voltage-source inverter can produce. These are shown in Figure 2.2

![Figure 2.2 Available stator voltage vectors.](image)

The analysis performed by the optimal switching logic is based on the mathematical spatial vector relationships of stator flux, rotor flux, stator current, and stator voltage. These relationships are shown as a vector diagram in Figure 2.3. The torque developed by the motor is proportional to the cross product of the stator flux vector (\(\Psi_s\)) and the rotor flux vector (\(\Psi_r\)).

![Figure 2.3 Stator spatial vector relationships](image)
The magnitude of stator flux is normally kept as constant as possible, and torque is controlled by varying the angle ($\delta$) between the stator flux vector and the rotor flux vector. This method is feasible because the rotor time constant is much larger than the stator time constant. Thus, rotor flux is relatively stable and changes quite slowly, compared to stator flux.

When an increase in torque is required, the optimal switching logic selects a stator voltage vector ($V_x$) that develops a tangential pull on the stator flux vector ($\Psi_s$), tending to rotate it counterclockwise with respect to the rotor flux vector ($\Psi_r$). The enlarged angle ($\delta$) created effectively increases the torque produced. When a decrease in torque is required, the optimal switching logic selects a zero-voltage vector, which allows both stator flux and produced torque to decay naturally. If stator flux decays below its normal lower limit the flux status output will again request an increase in stator flux. If the torque status output is still low, a new stator voltage vector ($V_x$) is selected that tends to increase stator flux while simultaneously reducing the angle ($\delta$) between the stator and rotor flux vectors.

Note that the combination of the hysteresis control block (torque and flux comparators) and the optimal switching logic eliminate the need for a traditional PWM modulator. This provides two benefits. First, small signal delays associated with the modulator are eliminated; and second, the discrete constant carrier frequencies used by the modulator are no longer present. [4]

E. Adaptive Motor Model

With reference to figure 2.1, it can be seen that the adaptive motor model is responsible for generating four internal feedback signals: 1) actual flux (stator); 2) actual torque; 3) actual speed; and 4) actual frequency. Dynamic inputs to the adaptive motor model include: 1) motor current from two stator phases; 2) link voltage; and 3) power switch positions. Static motor data is also utilized in making calculations. The static data come from two sources: 1) user input data and 2) information determined automatically from a motor identification run that occurs during commissioning.

The user input data include motor nominal voltage, motor nominal current, motor nominal frequency, motor nominal speed, and motor nominal power. The data collected during the motor identification run include motor inductances, stator resistances and stator saturation effects. [4]

F. Torque Production

![Figure 2.4 Estimated air-gap torque with hysteresis control.](image-url)
The estimated air-gap torque produced by the drive is shown in Figure 2.4. The periods during which torque has a positive slope, such as the region indicated as T+ in Figure 2.4, indicate intervals where an active stator voltage vector is causing torque to increase. The periods during which torque has a negative slope, such as the region indicated as T0 in Figure 2.4, indicate intervals where a zero-voltage vector has been selected. During most periods, either a simple positive slope or simple negative slope is indicated. During these periods, a single stator voltage vector selection has been able to satisfy both the torque status and the flux status output. However, during some periods, such as the region near the identifier Te, a dual slope is present. This is indicative of an interval during which, after one voltage vector has been chosen, and although additional torque still needs to be developed (i.e., the torque status output is not satisfied), a change in the flux status output has occurred that requires selection of another stator voltage vector.

Normally, switching occurs whenever torque drops below or exceeds In the special case where torque exceeds, the optimal switching logic selects a stator voltage vector that forces a decrease in torque by causing a reduction in the angle between the stator flux vector and the rotor flux vector. [4]

3. SIMULATION OF DTC

The complete simulation is sub divided as follows:
- DTC controller units
- Inverter
- Induction motor

![Figure 4.1 Block diagram of DTC for 3 phase IM drive](image)

A. DTC CONTROLLER UNITS

Figure 4.2 represents the subsystem for the DTC controller. The DTC controller unit takes motor currents $i_{sa}$, $i_{sb}$, and $V_{dc}$ as feedback signals to estimate flux and torque. The reference input may be speed reference or torque reference. In case of speed control mode, the speed control block is implemented with a traditional PI controller. The speed reference input is compared to actual speed feedback from the adaptive motor model. The resulting output signal becomes the reference for the torque controller. [4]
The torque controller has two inputs, the torque reference and absolute torque reference. In case of torque control mode, only the absolute torque reference is used.

These references are not used simultaneously. The control variables stator flux and motor torque are to be estimated accurately in real time. The maximum switching frequency is limited to 5 KHz. Therefore the switching signals to inverter are updated in every 200 µsec. For proper selection of switching signals the stator flux and torque need to be estimated 4 to 5 times during this interval. This implies that the flux and torque control algorithm should be executed once in 50 µsec. The output for this system is the switching signals Sa, Sb, & Sc.

**B. Speed Controller**

The speed controller block consists of traditional PI controller. The PI controller can be realized by using the integrator block and gain block as shown in figure 4.3. Approximately 75% of feedback controllers in the process industry are PI controllers. To remove the steady state offset in the controller variable, the PI controller is used.

The equation describing PI controller is as follows.

\[ u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int e(t) \, dt \right] \]

or \[ U(S) = K_p \left[ 1 + \frac{1}{T_i S} \right] E(S) \]

where

- \( K_p \) = controller gain
- \( E(t) \) = error signal
- \( U(t) \) = controller output
- \( T_i \) = integral or reset time.
The integral or reset time in this controller removes the steady state offset in the controller variable.

**C. Flux and Torque Estimation**

The two motor currents $i_{sa}$, $i_{sb}$ and $V_{dc}$ are taken as input signals. The flux and torque are estimation block is as shown in figure 4.4.

![Figure 4.4 Subsystem for Torque & Flux Estimation](image)

The magnitude of stator flux $\psi_s$ is obtained as:

\[
I_{\psi_s} = \sqrt{(\psi_{sa}^2 + \psi_{sb}^2)}
\]

\[
\psi_s = \tan^{-1}(\psi_{sa} / \psi_{sb})
\]

The sector block takes the angle information and determines the region of the flux phasor. The flux and torque are estimated once in every 50 µsec and is obtained by sampling the input signal at a frequency of 20 KHz.

**D. Flux Controller**

The flux controller is as shown in figure 4.5. This takes two inputs flux reference and flux estimated. These inputs are compared and the resulting output is given to the flux controller.

![Figure 4.5 Subsystem for Flux controller](image)

The flux controller hysteresis band is realized by using a relay block. The output ‘F’ takes the value 0 & 1.

For $[\psi_{s-ref} - \psi_{s-est}] > \Delta \psi_s / 2$, $F=1$ i.e. the increase in flux is commanded.

For $[\psi_{s-ref} - \psi_{s-est}] < -\Delta \psi_s / 2$, $F=0$ i.e. the decrease in flux is commanded.

Where,
ψ_s-ref = rated flux.
ψ_s-est = reference flux.

E. Torque Controller

The torque reference input is compared to the estimated torque and the resulting output is processed through the torque hysteresis controller. The torque controller has two relay blocks, which are representing the hysteresis for positive and negative values of torque reference; Md-ref. the output takes the values 0, 1, 2.

![Figure 4.6 Subsystem for Torque controller](image)

If \[ M_d-ref - M_d-est \] > \( \Delta M_d / 2 \) then, T=2 i.e.- command is given to increase the torque in CCW direction.
If \( \Delta M_d / 2 < [M_d-ref - M_d-est] > \Delta M_d / 2 \) then, T=1 i.e.- command is given to reduce the torque by switching zero vector.
If \[ M_d-ref - M_d-est \] < \( \Delta M_d / 2 \) then, T=0 i.e.- command is given to increase the torque in Clockwise direction.

Where,
\( M_d-ref \) = reference value of torque.
\( M_d-est \) = rated value of torque.
\( \Delta M_d \) = torque band.

F. Optimal Switching Block

Processing of torque status output and the flux status output is handled by the optimal switching logic. The function of this is to select the appropriate stator voltage vector that will satisfy both torque and flux status output.

This block takes the inputs F, T & R(n) from flux controller, torque controller & sector blocks respectively and determines the switching signals according to table 4.1 which is stored in the form of look up tables SWA, SWB & SWC. This block is shown in figure 4.7.

![Table 4.1](image)
Following assumptions are made for the simulation of inverter:

- The dc bus voltage is assumed to be constant. Since, three phase ac is converted to dc using simple diode rectifiers, the dc bus voltage may vary because of variation in the supply voltage & change in the inverter load.
- The inverter switching devices are assumed to be ideal. i.e.- the ON state voltage drop across the device, the turn on time & turn off time are neglected.

With these assumptions the inverter block is a simple gain block as shown in figure 4.8. The switching frequency of the inverter is limited to safe value of about 5 KHz.

An accurate dynamic model of the motor, which can explain the dynamic behavior of the machine at transient and steady state, is necessary. In DTC the control variables the stator flux and torque are expressed in terms of stator variables. So the motor model based on stationary reference frame is used. The stator and rotor current phasors \( I_s \) and \( I_r \) can be obtained by solving following set of equations. The subsystems of the induction motor is shown in figure 4.9.
4. SIMULATION RESULTS AND DISCUSSION

The Simulation results for DTC for three phase induction motor drive are obtained by running the simulation model with suitable simulation parameters.

The simulation results obtained mainly deal with the dynamic performance of DTC drive.

**Speed Control Mode of DTC Drive**

In this mode of operation, the reference speed is compared with actual speed, which is estimated by the adaptive motor model and the resulting speed error will be given to a PI controller, which will minimize the speed error to zero and generates a torque (speed) reference, which drives the motor to its desired speed under the maximum torque condition. Hence the torque developed will track its reference value to accelerate the motor to the reference speed. Once the motor reaches the desired speed no further
acceleration torque is required and hence torque curve falls to a value equal to sum of load torque and friction torque.

During starting, the estimated flux and torque are zero because the feedback data is not available for adaptive motor model. So the output of flux controller will be 1 and output of torque controller will be 1 (for clockwise direction) and -1 (for anticlockwise direction). Motor will draw very high current. This is not applicable. This problem can be minimized by establishing a low level DC flux, so that the stator current during starting can be kept under safe limit. In order to obtain the initial feedback a low level DC flux is established in motor.

This level is low enough that over current tripping and inappropriate torques are not created and high enough meaning feedback data is received. Once valid feedback is available, operation proceeds as previously explained.

Below base speed operation

In this mode of operation, the speed can be varied up to base value and at any reference speed it is possible to obtain the breakdown torque. The flux is maintained at its rated value. The region of operation is said to be constant torque region.

Figure 5.1 shows the speed, torque, stator current and flux curves in speed control mode, below base speed, with limit on maximum frequency of inverter set at 5 kHz. From the speed response curve as in figure 5.1(a) it is clear that the drive will track the reference speed at maximum torque (breakdown torque). The drive has taken around 0.3 sec to reach the rated speed of 1460 rpm. Hence the dynamic speed response of the drive is excellent as compared to other conventional and scalar control methods.

It can be observed from waveform of figure 5.1(b) that the torque ripple at steady state is large. This is due to fact that even though the controllers are in a position to correct the torque, the switching pulses are updated only once in 200 microseconds. This shows that by updating the pulses once in 200 microseconds, it is not possible to reduce the torque ripple less than certain value. A better approach to reduce the switching frequency and torque ripple simultaneously is to keep track of the inverter switching frequency and dynamically adjust the torque band. From the stator current curve as in figure 5.1(c) it is clear that during starting and step change in speed, the peak value of $i_{sa}$ is within limit.

For higher speeds, above base speed values, the stator voltage is kept constant and the frequency is increased beyond its base value so that motor operates in depth flux weakening region. This region of operation is said to be constant power region. In this region the developed torque goes on decreasing as speed increases. Figure 5.1 shows speed, torque, stator current and stator flux response for a supply frequency of 100 Hz in speed control mode of DTC drive.
V. CONCLUSION

Direct Torque Control combines the benefits of direct flux and direct torque control into sensorless variable frequency drive that does not require a PWM modulator. Recent advances in DSP and ASIC technology, plus the theoretical concepts developed for direct self control, make this possible. The theory of DTC for three phase Induction Motor Drive is developed. The mathematical model of the drive is developed and simulated. From the simulation transient and steady state performance of the drive is obtained. Following are some of the observations.
The results confirm the excellent dynamic response of the drive. For the system under consideration a step change in torque is achieved in 0.02 sec.

At steady state there is a ripple in the torque. This ripple depends on the switching frequency of the Inverter, which is determined by the torque band and flux band. The torque ripple cannot be reduced below a certain value because of maximum switching frequency limits of the Inverter.

The switching frequency of the inverter varies over a wide range. The switching frequency can be controlled by dynamically adjusting the torque and flux band.

Suitable method has to be developed to control the starting current of the motor.

The induction motor does not need rated flux at light loads. Since direct flux control is achieved in DTC, the flux can be reduced at light loads. Hence the heating of the motor can be reduced and efficiency of motor can be improved.

The DTC offers excellent dynamic performance. The limitations on the system are imposed by the inverter and not by the controller. It may be predicted that the DTC will be the most preferred control algorithm for AC drives.

REFERENCES

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